

# A Spectral Diagnostic for Density-Bounded H II Regions

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## 1 Abstract

The existence of density-bounded H II regions in spiral galaxies is supported by means of a spectral indicator based on the intensity of the [O I]  $\lambda 6300$  Å forbidden line. A grid of photoionization models providing spectral information of density-bounded nebulae is presented in order to test the validity of our indicator. The indicator is applicable to typical observed H II regions with solar or higher metallicities, and for the range of ages observed in normal H II regions. When applying the diagnostic to a large sample of H II regions of spiral galaxies taken from the literature, we find that a fraction of the selected H II regions with emission detected in the [O I]  $\lambda 6300$  Å line turn out to be consistent with the predictions of density-bounded photoionization models. Preliminary estimates of the fraction of Lyman continuum photons escaping ranges from 20% to 40%. The number of density-bounded H II regions could be even larger after confirmation of those regions for which the [O I] line was not detected, provided they are good density-bounded candidates. We stress the importance of having combined information on both good measurements or reliable upper limits for the intensity of this line, and good determinations of the H $\alpha$  luminosity for complete samples of H II regions in galaxies in order to make proper estimations as to whether UV photons escaping from H II regions are the main source of ionization of the diffuse ionized medium in galaxies.

## 2 Introduction

H II regions are clouds of ionized gas surrounding young massive stars. Their spectra are dominated by emission lines corresponding to H, He, and some forbidden lines of heavier elements. Their physics is well known, and has been reviewed by several authors (e.g., Spitzer 1978; Osterbrock 1989). In the classical view, H II regions are spheres of ionized gas illuminated by a star or a stellar cluster emitting Lyman continuum photons. The extent of the region is determined by the ionization front, where there is a balance between the number of photoionizations and recombinations of hydrogen atoms. When the H I cloud is large enough to consume all ionizing photons, the ionization front is trapped, and the H II region is said to be ionization bounded. Otherwise, there is no ionization front and some Lyman continuum photons eventually leak from the parent cloud. The region is then considered to be density bounded.

The real picture shows that stars are normally born in the inner cores of dense molecular clouds. Thus, density gradients are expected along the paths of Lyman continuum photons. The steeper the gradient, the larger the external radius of the ionized region is. During the expansion phase, for a density gradient larger than about  $R^{-1.5}$ , the ionization front is not trapped and many Lyman continuum photons are expected to leak from the parent cloud (Franco, Tenorio-Tagle, & Bodenheimer 1990).

From optical emission-line and pulsar dispersion measurements in the Milky Way, we know now that most of the ionized gas is located in very low density (more than ten times lower than in classical H II regions) clouds far from star clusters, even several hundreds of parsecs above galactic disks. This ionized component would be mixed with the neutral one and would constitute one-third of the total mass of the interstellar medium. So, although recombinations are mainly associated with star clusters, most of the mass of H II regions is associated with an extended low density component (see Reynolds 1993 for a review of the main properties of the diffuse interstellar medium in our Galaxy). Observations of diffuse ionized gas in the disks of spiral galaxies has led to the conclusion that many ionizing photons should escape from the H II regions, producing a diffuse ionized component

(Ferguson et al. 1996).

Several authors have reported the existence of such density-bounded H II regions. The observational evidence is based on different considerations such as the non-correlation between the stellar and H $\alpha$  luminosities measured for H II regions (Oey & Kennicutt 1998), the change in the slope of the H $\alpha$  luminosity function for the brightest H II regions (Beckman, Rozas, & Knapen 1998), changes in the  $L(\text{H}\alpha)$  vs.  $\sigma$  diagram (Fuentes-Masip et al. 2000) for H II regions in irregular galaxies, or discordant emission lines with respect to photoionization models (Castellanos et al. 2002).

We address the topic by studying the very faint [O I]  $\lambda 6300$  Å emission line. Since most of the [O I] emission arises from collisional excitations by thermal electrons via the charge exchange reaction  $\text{H}^+ + \text{O}^0 \longleftrightarrow \text{H}^0 + \text{O}^+$ , its intensity is a measure of the neutral hydrogen content within the ionized regions. Although in typical H II region conditions the charge exchange has a rate comparable with recombination in converting  $\text{O}^+$  to  $\text{O}^0$ , charge exchange dominates at the outer edges of the nebulae because of the higher density of  $\text{H}^0$  (see Osterbrock 1989). Therefore, the detection of the [O I] line in the spectrum of an H II region indicates that most (if not all) of the Lyman continuum photons are absorbed by the nebula. In an ideal H II–H I discontinuity there would be a shell of [O I] delimiting the border of the H II region.

In this paper we describe a method for determining whether H II regions with solar or higher metallicity are density or ionization bounded, based on the intensity of the [O I]  $\lambda 6300$  Å line. A grid of photoionization models has been constructed and is described in Section 3. Section 4 shows diagnostic diagrams applied to the output spectra in order to explore the influence of escaping Lyman continuum photons in the spectra of H II regions. Finally, Sect. 5 contains some discussion of the main results of the paper and their application to a sample of H II regions in nearby spiral galaxies.

### 3 The Grid of Models

A grid of models was constructed using the latest version of the photoionization code CLOUDY (see Ferland 1993 for details). Each model is parameterized by the hydrogen density, the ionization parameter, the shape of the central stellar continuum—including age and the slope of the initial mass function (IMF) effects—and the chemical composition. Table 1 shows the different values adopted.

Given the lack of geometrical information available for most H II regions in spiral galaxies, and that there exists a relationship between the number of ionizing photons, the density of the nebula and the filling factor<sup>1</sup>, fixed values of the hydrogen density and the ionization parameter were assigned to each model. The number of ionizing photons is a free parameter, as are some geometrical quantities. The hydrogen density was set at  $10 \text{ cm}^{-3}$  for all models below the limit for collisional de-excitation of the important cooling lines, and the ionization parameter ( $\log u$ ) ranged from  $-2$  to  $-4$  (inclusive).

The chemical composition was chosen to cover a wide range of oxygen abundances, from  $0.1 Z_{\odot}$  to  $2 Z_{\odot}$ , according to the solar abundance of oxygen relative to hydrogen defined by Anders & Grevesse (1989). The relative abundances of the other metals were scaled to that of oxygen following the prescription for H II regions (see Ferland 1993, for details). The effects of dust were not considered.

Finally, we chose the spectral energy distributions (SEDs) from Leitherer & Heckman (1995) as ionizing sources, in such a way that their metallicities matched those of the ionized gas. The IMFs chosen were those of Salpeter ( $\alpha = -2.35$ ), with upper limits of 30 and  $100 M_{\odot}$ , and Miller Scalo ( $\alpha = -2.35$ ), with  $M_{\text{up}} = 100 M_{\odot}$ . Given that the shape of the ionizing continuum changes with the age of the cluster, we run the code for ages between 1 and 10 Myr, with intervals of 1 Myr.

The grid of models chosen covers the whole parameter space of the ob-

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<sup>1</sup> $u \propto (Q_{\text{H}} n \epsilon^2)^{1/3}$ , where  $u$  is the ionization parameter,  $n_{\text{H}}$  is the hydrogen density,  $\epsilon$  is the filling factor and  $Q_{\text{H}}$  is the number of ionizing photons.

served H II regions. Given that we want to study the effect of density-boundedness in the spectra of H II regions, we produced both ionization-bounded and density-bounded models. The ionization-bounded models are those for which the radiation transfer is computed until the temperature of the nebula is 2500 K. At this point the fraction of ionized hydrogen is negligible and we may consider all the Lyman continuum photons to have been absorbed by the nebula. After that, for each ionization-bounded model we produce a density-bounded model with the same input parameters as the corresponding ionization-bounded model, but we stop the computation of the radiative transfer at the point where the abundance of  $O^0$  reaches one-tenth of the value measured at the border of the corresponding ionization-bounded model. Of course, the fraction of escaping photons is not the same for all models and strongly depends on the value of  $u$  assumed for each model. At the point we stop the computation of the radiative transfer across the nebula, CLOUDY provides all the required information to estimate the fraction of escaping photons as well as the emergent spectrum for each density-bounded model.

## 4 Diagnostic Diagrams

First, we tested the reliability of the models with a classical diagnostic diagram for observed H II regions. Figure 1 shows the diagram representing  $\log ([O II] + [O III])/H\beta$  vs.  $[O III]/[O II]$ . The shaded region corresponds to the locus occupied by the H II regions observed by McCall, Rybski, & Shields (1985). The open and close squares correspond to ionization-bounded and density-bounded models, respectively, chosen arbitrarily from our set. It is clear from the figure that both ionization- and density-bounded models coexist within the region occupied by the observed H II regions. This means that the strongest emission lines of oxygen do not provide enough information to discriminate between density-bounded and ionization-bounded H II regions.

With the aim of finding an indicator of photon leakage in H II regions, as mentioned in Sect. 1, we focus our work on the forbidden  $[O I] \lambda 6300\text{\AA}$  emission line. In Fig. 2 we plot the fractional abundances of the most abundant ions of oxygen for a particular model of our grid, vs. the radial thickness,

which is the distance to the inner face of the ionized shell. The continuum line represents  $O^0$ , the dashed line  $O^+$ , and the dot-dashed line  $O^{++}$ . As shown in the figure, the  $O^{++}$  ion is dominant throughout most of the radial profile of the nebulae. It shows a sharp cut-off almost at the external boundary, where the  $O^+$  and especially  $O^0$  become dominant. At the edge of the ionized nebula, even the  $O^+$  ion decays. Although the width of the  $O^0$  region and the steepness of the transition strongly depend on the physical properties of the nebula (ionization parameter, shape of the stellar continuum, metallicity) the qualitative behaviour is essentially as described above for all cases. The lower plot shows the emissivity of the  $O^0$  ion as a function of radial thickness. It can be seen that the maximum is reached in the outermost ionized layers. So this plot is telling us that  $O^0$  is an excellent tracer of the HII region boundary. The emergent flux of the  $[O\text{ I}] \lambda 6300 \text{ \AA}$  emission line should decrease as the escape of Lyman continuum photons increases.

Figure 3 shows the  $[O\text{ I}]/H\beta$  ratio as a function of  $[O\text{ II}]/H\beta$  for our set of models. Given the range in age measured for optically detected H II regions (see Martin & Friedly 1999), only models with ages of between 2 and 9 Myr are represented. Plot (a) corresponds to models with metallicities equal to or greater than solar, and plot (b) corresponds to models with subsolar abundances. In both plots, solid, dashed and dot-dashed lines represent the ionization-bounded models with different IMFs. Each line corresponds to the subset of models with a given age, IMF, and metallicity, covering all possible values of the ionization parameter. Crosses and diamonds represent those density-bounded models with fractions of escaping Lyman continuum photons of 20% and 40% respectively; these were plotted in order to compare their position in the diagram to that of the ionization-bounded models.

As can be seen from Fig. 3(a), most ionization-bounded high-metallicity models, follow a linear trend in the plot with a slope of approximately unity. These models correspond to H II regions for which most of the oxygen is doubly ionized, the  $O^{++}$  zone almost reaching the outer limit of the nebula. The role of the ionization parameter is limited in regulating the relative widths of the  $O^+$  and  $O^0$  zones of the nebula, which are confined to the outermost layers. Thus, as soon as the degree of ionization decreases, the  $O^0$  fraction increases producing a dramatic decrease in the  $O^+$  fraction, which is far less important than that of  $O^{++}$ . Thus, the fluxes of the emission lines

from both ions are linearly related.

For other ionization-bounded models, the [O I] and [O II] fluxes are almost unrelated and correspond to H II regions where the  $O^+$  ion is dominant throughout, except in the outer boundary, where the  $O^0$  is always dominant. The contribution of the [O II] line comes from a highly extended region compared to that of the [O I] line, and thus the flux of the [O II] line remains almost unchanged with small changes in the flux of the [O I] line.

The two different trends shown by the ionization-bounded models is understood in terms of the presence of an excess of energetic photons in the ionizing SED coming from Wolf-Rayet (WR) stars. In fact, these are models for which the fraction of WR to O stars is non-negligible, and which show the linear unity-slope trend previously mentioned. These stars appear only for a short time period of between about  $3 \times 10^6$  to  $6.5 \times 10^6$  yr and contribute significantly to the total number of ionizing stars for metallicities of the order of solar or higher (see Leitherer & Heckman 1995 for details). Of course, the assumed upper mass limit of the IMF plays an important role in determining whether or not models with the same physical parameters follow the linear trend, since for an IMF with  $M_{\text{up}} = 30 M_{\odot}$  the beginning of the WR phase is delayed by some 3 Myr. However, for the range of ages displayed in the plot, this result holds regardless of the upper mass limit assumed for the IMF.

The density-bounded models tend to show almost similar fluxes in the [O II] line to those corresponding to ionization-bounded models, but with significantly lower fluxes in the [O I] line, and thus populate the region below this linear trend. There is significant overlapping between both ionization-bounded and density-bounded models. However, there is an area below the linear trend—the shaded region in the plot—with no overlap between both sets of models and populated only by density-bounded models. The existence of only density-bounded models in this region suggests that H II regions populating this region should be the density-bounded ones.

The result is not so clear for low metallicity models. Figure 3(b) shows that both sets of models appear to be mixed throughout the diagram, and only a very small region—shaded in the plot—appears to be populated only by density-bounded models, thus making this diagnostic useless.

Another process that can play a role in the intensity of the [O I]  $\lambda 6300$  Å line is the presence of shock fronts due to galactic winds and/or supernovae explosions. However, this mechanism tends to increase the intensity of the [O I]  $\lambda 6300$  Å line (Dopita & Sutherland 1996), thus producing the opposite effect to that produced by UV photon escaping from the nebulae. This means that the escaping photons fractions estimated from our models are lower limits to the real values if we assume the likely presence of shocks in these regions.

## 5 Discussion and Conclusions

In order to check the validity of the diagram presented in the previous section, we have used a large sample of observed H II regions. The sample selected (van Zee et al. 1998) comprises spectra for 186 H II regions belonging to 13 nearby spirals. In addition, the [O I]  $\lambda 6300$  Å line has been measured for many regions. For each region, abundances values are provided. We have selected those regions for which a value of  $12 + \log \text{O}/\text{H} > 8.7$  has been reported. We thus include the H II regions with metallicity higher than or of the order of solar, taking into account that the typical errors in the semi-empirical calibrations for the oxygen abundances are of the order of 0.10 dex.

In particular, the high-metallicity regions are located towards the centres of spiral galaxies (see van Zee et al. 1998 and references therein for comments about the metallicity gradients measured for their sample galaxies). Also, studies of complete populations of H II regions in spiral galaxies show that most of them are located in the inner regions with a maximum at about  $0.25 R_{25}$  with an outward exponential decrease (Rozas et al. 1996). In addition, Fergusson et al. (1998) showed that although H II regions can be found as far out as two optical radii, they appear small and faint compared to their inner-disk counterparts. So taking all the three remarks together suggests that our diagnostic is of general utility for H II regions in spiral galaxies, and that many of the brightest ones should fulfil the requirements to be checked with our diagnostic.

Figure 4 shows the [O II] vs. [O I] diagnostic diagram for the selected



subsample of H II regions. Thick crosses represent the observed H II regions. Error bars from van Zee et al. (1998) are also plotted. H II regions with no detected emission from the [O I]  $\lambda 6300$  Å are represented with downward-pointing arrows. Solid lines correspond to the ionization-bounded models. The shaded region corresponds to the area occupied by density-bounded models with no overlap with ionization-bounded models.

As this figure shows, many observed H II regions lie within the shaded region which corresponds to the area occupied by density-bounded models and with no overlapping with the ionization-density models (in particular, 80% of those for which the [O I]  $\lambda 6300$  Å line was detected). If we also take into account the regions for which this line was not detected, the fraction of H II regions lying within the shaded region or just below amounts to 70%. According to the position occupied by the density-bounded models in Fig. 3(a), the estimated fraction of Lyman continuum photons escaping from the H II regions falling in the shaded region ranges between 20% and 40% although this proportion could be even more pronounced if other mechanisms that enhance the intensity of the [O I] line are present. Of course, a more precise determination of the fraction of escaping Lyman continuum photons needs an accurate fit of the complete spectra of the observed H II regions to individual models.

Concerning the negative detections, 64% of these fall just below the shaded regions, which means that they fulfil the applicability conditions of our diagnostic on detection of the [O I]  $\lambda 6300$  Å line. If the absence of the [O I]  $\lambda 6300$  Å line is caused by lack of sensitivity, nothing can be said about the fraction of escaping UV photons; but if it is caused by real density-boundedness, fractions of UV photons even greater than 40% could be escaping from the H II region. In any case, more detailed studies of individual spectra are required for these H II regions.

We should emphasize that the available data for the H II regions in the sample that we have used are integrated and thus do not take into account the possible irregular morphologies of the regions. Therefore, it could be that H II regions are only partially density bounded, probably on the side orientated towards lower densities in the molecular clouds, and that what we are measuring is just an average effect. In order to go deeper into the study

of the structure and porosity of H II regions, spectral data on the individual shells of spatially resolved H II regions are required in order to check whether or not Lyman continuum photons are escaping through the ionized shells.

In this paper we have presented evidence supporting the hypothesis that density-bounded H II regions do exist in spiral galaxies. The emission from the [O I]  $\lambda 6300$  Å line combined with that of the [O II]  $\lambda\lambda 3727, 3729$  Å doublet is a good diagnostic for discerning whether high metallicity H II regions are density or ionization bounded. A preliminary study of a sample of H II regions in spiral galaxies shows that some high metallicity H II regions confirm the predictions of density bounded photoionization models, with fractions of escaping Lyman continuum photons ranging between 20% and 40% (but the fraction could be higher for H II regions for which we do not have information about the intensity of the [O I]  $\lambda 6300$  Å line). However, it is not clear whether the number of density-bounded regions and the fraction of Lyman continuum photons escaping from them are enough to provide the observed ionization of the diffuse medium, while we have no information on the [O I]  $\lambda 6300$  Å line for a complete sample of H II regions. Combined information on the spectra and H $\alpha$  luminosity of complete samples of H II regions in galaxies are needed to at least set a lower limit to the number of ionizing photons escaping from H II regions. In fact, the breakout of ionized shells proposed by Tenorio-Tagle et al. (1997), might be an even more important contributor to the ionization of the diffuse intergalactic medium.

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Parameter	Values
$12 + \log \text{O}/\text{H}$	8.3, 8.6, 8.9, 9.3
$\log u$	-2.0, -2.5, -3.0, -3.5, -4.0
$\alpha$	-2.35, -3.30
Age (Myr)	1, 2, 3, 4, 5, 6, 7, 8, 9, 10
$M_{\text{up}} (M_{\odot})$	30, 100

Table 1: Physical parameters of the models.

Figure 1: The shaded area corresponds to the region occupied by the measured H II regions from McCall et al. (1985). Open squares correspond to models of our grid representing ionization-bounded H II regions. Filled squares correspond to the models representing density-bounded H II regions with the same physical parameters.

Figure 2: The upper plot shows the fractional abundances of the different ions of oxygen as a function of the radial thickness for a particular model of our grid. The lower plot shows the emissivity of the  $O^0$  ion as a function of the radial thickness for this model.

Figure 3: (a)  $[O\text{ I}]/H\beta$  vs.  $[O\text{ II}]/H\beta$  diagram for ionization-bounded models (solid lines for  $\alpha = -2.35$  and  $M_{\text{up}} = 100 M_{\odot}$ , dashed lines for  $\alpha = -2.35$  and  $M_{\text{up}} = 30 M_{\odot}$  and dash-dotted lines for  $\alpha = -3.30$  and  $M_{\text{up}} = 100 M_{\odot}$ ). Crosses and diamonds represent density-bounded models with 20% and 40% escaping Lyman continuum photons respectively. The shaded region represents the loci expected for the density-bounded H II regions. Only models with metallic abundances equal to or greater than solar were considered in this plot.

Figure 3: (b) Same as Figure 3(a) for models with subsolar metal abundances.

Figure 4: Same as Figure 3. Solid lines correspond to ionization-bounded models with metal abundances equal to or greater than solar. Crosses correspond to the high-metallicity H II regions from van Zee et al. (1998). Downward-pointing arrows represent those H II regions with no flux reported for the [O I]  $\lambda 6300$  Å line. The shaded region corresponds to the loci occupied by density-bounded models.